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Development and Demonstration of a Custom Cryogenic Grinding Process for Rubber and Plastic Recycling

Canada

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Environmental Impact Control Directorate
December 1982

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DEVELOPMENT AND DEMONSTRATION OF A CUSTOM CRYOGENIC GRINDING PROCESS FOR RUBBER AND PLASTIC RECYCLING

by

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Custom Cryogenic Grinding Corp.

for

Waste Management Branch
Environmental Impact Control Directorate
Environmental Protection Service
Environment Canada

This project was conducted under the Development and Demonstration of Resource and Energy Conservation Technology (DRECT) Program

DRECT

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et demander:

Conception et mise au point d'un procédé de recyclage du caoutchouc et de plastiques par voyage cryogénique

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ABSTRACT

Most plastic and rubber processes unavoidably generate scrap material (73 tonnes per day in Ontario). As raw material prices continue to increase, so do incentives to recycle scrap. Many plastic processors are able to recycle scrap by granulating it to a chip or pellet size. However, many other plastic and rubber manufacturers require a much smaller particle size for recycling purposes. In most cases the desired product characteristics can only be attained economically by cryogenic grinding.

The objective of this project is to demonstrate the economic and technical viability as well as the energy savings and resource recovery potential of a system for cryogenic recycling of plastic and rubber waste.

To demonstrate the process, the Custom Cryogenic Grinding Corporation was formed and a cryo-grind facility was established on January 1, 1980 at 1730 McPherson Ct., Unit No. 5, in Pickering, Ontario.

Test data and economic evaluation indicate that the reuse of cryo-ground polymer can provide significant savings on raw material and disposal costs.

The reuse of 680 tonnes per year of polymer recycled by cryogenic grinding could displace approximately 1.9×10^6 L of oil.

RÉSUMÉ

La transformation du caoutchouc et des plastiques entraîne la production inévitable de déchets (73 tonnes par jour en Ontario). Comme le prix des matières premières augmente continuellement, il devient de plus en plus impérieux de recycler ces rebuts. Plusieurs procédés de recyclage sont capables de transformer les déchets des plastiques en granules ou en copeaux, mais de nombreux fabricants de caoutchouc et de plastiques préfèrent des particules beaucoup plus fines. Dans la plupart des cas, il faut alors faire appel au broyage cryogénique pour obtenir les caractéristiques voulues à un coût raisonnable.

Par ce projet, nous avons voulu démontrer qu'il est techniquement et économiquement possible d'utiliser un système cryogénique pour le recyclage des déchets du caoutchouc et des plastiques, tout en consommant moins d'énergie et en utilisant mieux nos ressources.

Pour démontrer la valeur du procédé envisagé, une corporation, la Custom Cryogenic Grinding Corp, fut créée et des installations de broyage cryogénique furent établies à compter du premier janvier 1980 au 1730 McPherson Ct, Unit No. 5, à Pickering (Ont.).

Les résultats de nos essais et de notre étude économique indiquent que l'utilisation de polymères broyés à froid permet de réaliser des économies importantes en matières premières et de réduire les coûts d'élimination des déchets.

Le recyclage de 680 tonnes par année de polymères à l'aide du procédé de broyage cryogénique pourrait permettre d'utiliser environ 1,9 x 10^6 l de pétrole à d'autres fins.

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1 BACKGROUND

It has been estimated that 75% of the natural resources now being thrown away in the nation's waste system can be reclaimed and recycled. Cryogenics, a branch of physics that relates to the production and effects of very low temperatures, can play an important part in the recovery of many of these resources.

The fundamental principle of this cryogenic recycling process involves embrittling a waste material by cooling to very low temperatures and then fracturing the material into small particles. Temperature is the key to the whole process. Some materials, including many plastic and rubber materials, become brittle when exposed to freezing agents like liquid nitrogen (-196°C). In the brittle state, these materials are easier to grind and produce a smaller particle size than at room temperature where they are found to be tough and extremely difficult to comminute.

To determine what kind of polymer is a good candidate for cryogenic recycling, the following physical properties are addressed:

- a glass-transition temperature below room temperature at which the amorphous content of the waste material becomes brittle;
- high tendency to fracture, which depends upon the percent crystallinity and the nature of arrangement in the crystal lattice; thus, highly crystalline and oriented fibers do not fracture readily;
- presence of ultra-high molecular weight species, incorporation of 1% of which may increase fracture toughness 3 to 10 times;
- nature of fillers used: inert fillers decrease fracture toughness whereas fibers increase it;
- polarity of polymers: high-polarity polymers are difficult to fracture;
- types of monomers and their relative percentage in case of copolymers and terpolymers;
- in the case of films and laminates, the thickness of coatings can determine fracture properties. For a flexible substrate, a very thin coating is difficult to fracture.

For those materials which do fracture, cryogenic grinding is ideal for producing small-particle, free-flowing powders at reduced costs with no deterioration in product quality. Furthermore, this cryogenic process has some attractive features inherent in its use of liquid nitrogen. These are:

- the use of liquid nitrogen as a freezing medium is ecologically sound since it is non-polluting and is produced from relatively non-polluting liquid air plants;
- liquid nitrogen is relatively inexpensive when used in large quantities and is abundantly available and easily shipped;
- the boiling point of liquid nitrogen, -196°C, is lower than that of most materials. Therefore, a large variety of materials can be processed;
- the liquid nature of the nitrogen, which allows for rapid contact with the material, plus the rapid boiling provide high heat transfer coefficients so that materials can be cooled quickly and simply. This allows the procedure to be utilized in large-scale processing;
- since cryogenic freezing is a physical process, normally no chemical reactions will occur with the waste material. Hence the processed waste is not converted into other chemical species;
- the production of particulates from the process allows for easy handling and separation of the treated waste. A wide range of readily controlled particle sizes can be obtained depending on a number of mechanical factors.

To demonstrate the process, the Custom Cryogenic Grinding Corp. was formed and a cryo-grind facility was established on January 1, 1980, at 1730 McPherson Ct., Unit No. 5, in Pickering, Ontario.

2 PROCESS

Custom Cryogenic Grinding Corp. uses the patented Air Products and Chemicals Inc. "Cryo-Grind" size-reduction process shown schematically in Figures 1 and 2. Scrap, in the form of sprues, end-cuts, flash or transfer pads is first reduced in a granulator to small chips (about 6 mm). The chips are more easily handled, are relatively free-flowing, and have better heat transfer characteristics.

The chips are fed into a loading hopper, then enter a cooling conveyor where liquid nitrogen at -196°C is sprayed directly onto the material. The liquid nitrogen vapourizes to a gas by absorbing the required heat of vapourization from the feed material. Seeking thermal equilibrium, the cold nitrogen gas continues to cool the feed material to its embrittlement point. In this state the material can be fractured easily. A thermocouple and a temperature indicator are used to monitor the temperature within the cooling conveyor and the grinding mill discharge hopper.

After leaving the cooling conveyor, the material is introduced into a grinding mill by way of a feedscrew assembly, where the embrittled material is ground to a powder. During the grinding stage, additional liquid nitrogen may be injected into the mill to remove the heat generated by the impact energy applied to the material. If this heat of grinding were not removed, the material temperature could rise above the embrittlement point, resulting in little or no fracture and possible degradation and melting. The ground material exits the grinding mill through openings in a discharge screen, the size of which affects the particle size distribution. A thermocouple located directly below the discharge screen of the grinding mill is used to sense the temperature within the grinding chamber.

A standard "Cryo-Grind" system installation consists of the following:

a. an Air Products "Cryo-Grind" cooling conveyor to cool the material to below its embrittlement temperature;
b. a grinding mill to reduce the embrittled feed material to smaller particle sizes, usually a hammermill or attrition mill;
c. an Air Products "Cryo-Grind" integrated control panel to control all system equipment; and
d. an Air Products liquid nitrogen flow control system to deliver liquid nitrogen to the "Cryo-Grind" system.

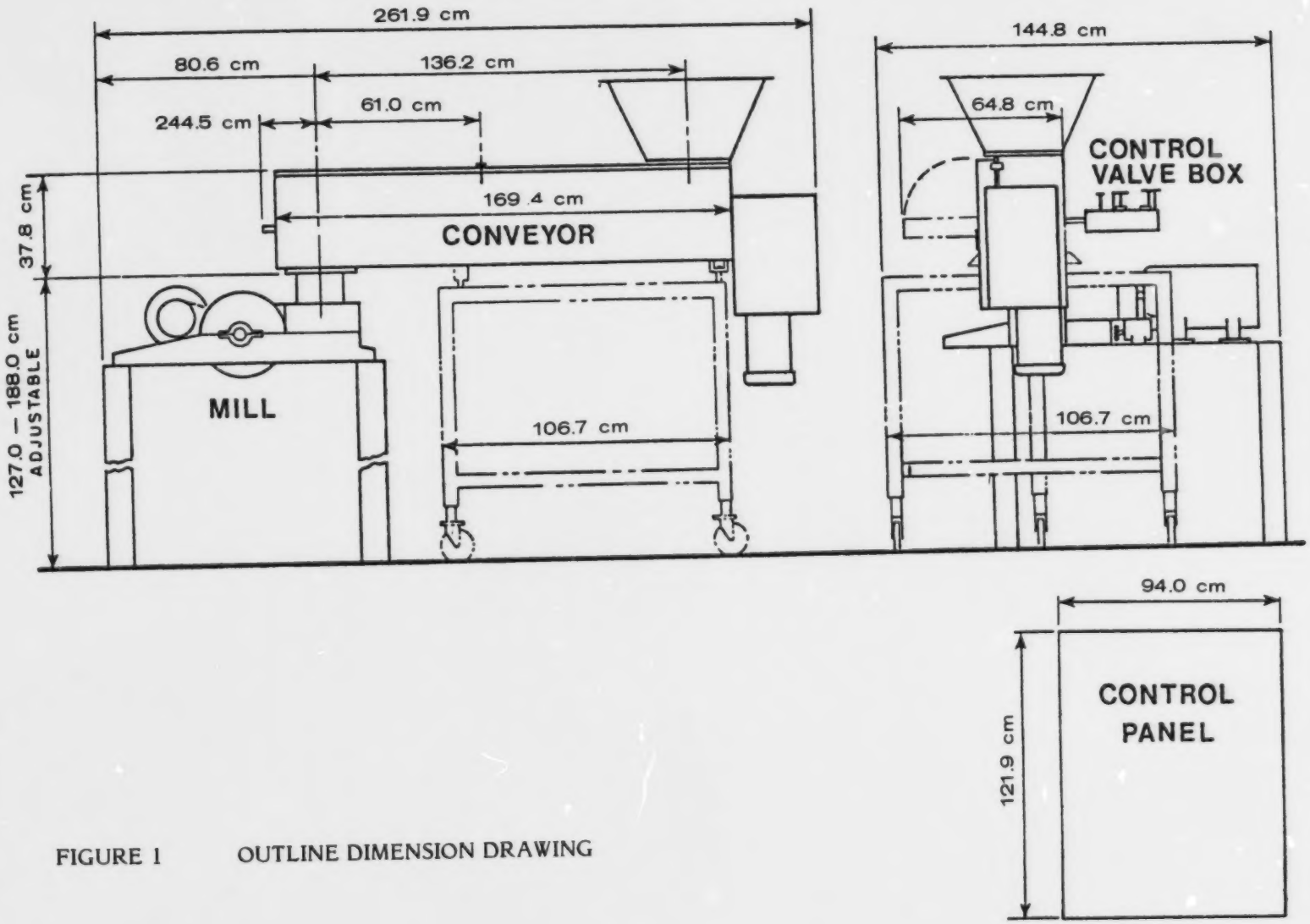


FIGURE 1 OUTLINE DIMENSION DRAWING

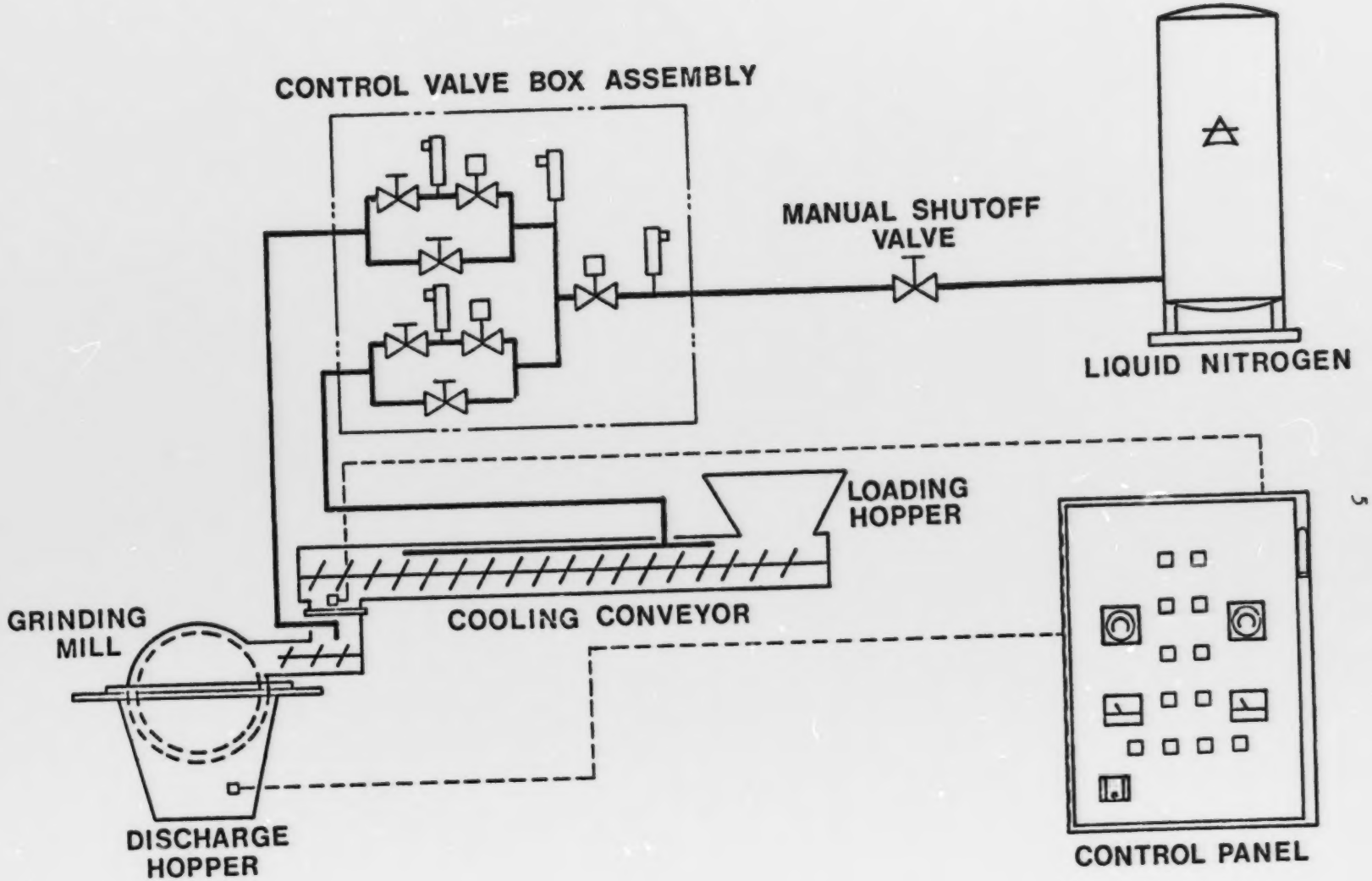


FIGURE 2 FLOW SCHEMATIC

2.1 Features

Standard features of the Air Products "Cryo-Grind" system are listed below:

a. Control Panel: completely automatic with a temperature control system and an ammeter controller for mill overload protection.

b. Stainless Steel Cooling Chamber: specially designed stainless steel conveyor screw and impeller; removable conveyor screw for easy cleaning; highly efficient thermal insulation; side opening door for easy cleanout; variable speed drive motor; conveyor door safety interlock.

c. Adjustable Conveyor Support Stand: mount holes for optional actuator.

d. Stainless Steel Feed Hopper with 0.25 m^3 Capacity.

e. Control Valve Box Assembly.

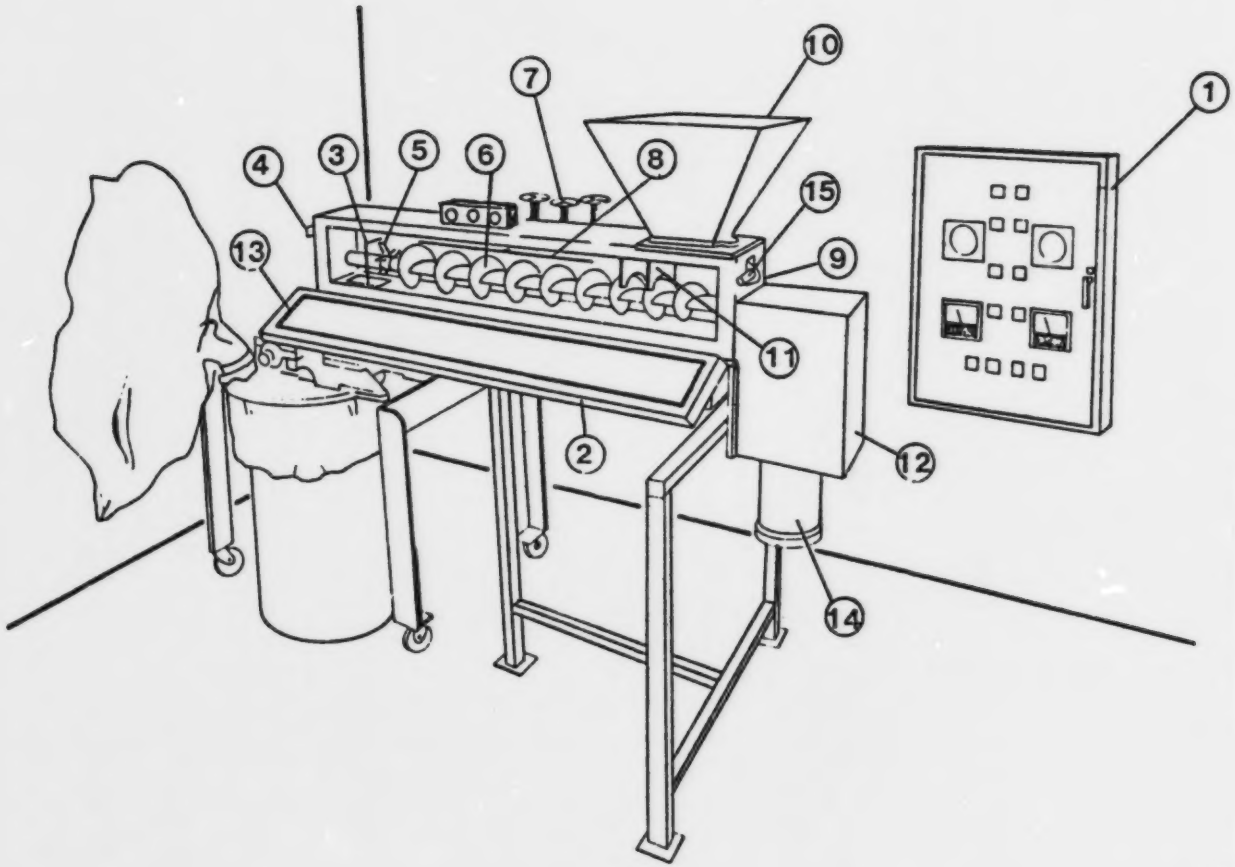
f. Mikro-pul Model 2DH Pulverizer: all guards meet OSHA specifications; all parts that contact product are stainless steel; multiple deflector liner; mill head safety interlock.

The "Cryo-Grind" system is made of durable materials, requires little maintenance and operates efficiently at cryogenic temperatures. It is designed for easy cleanout and the cooling conveyor is fully insulated to conserve liquid nitrogen.

2.2 Major Components

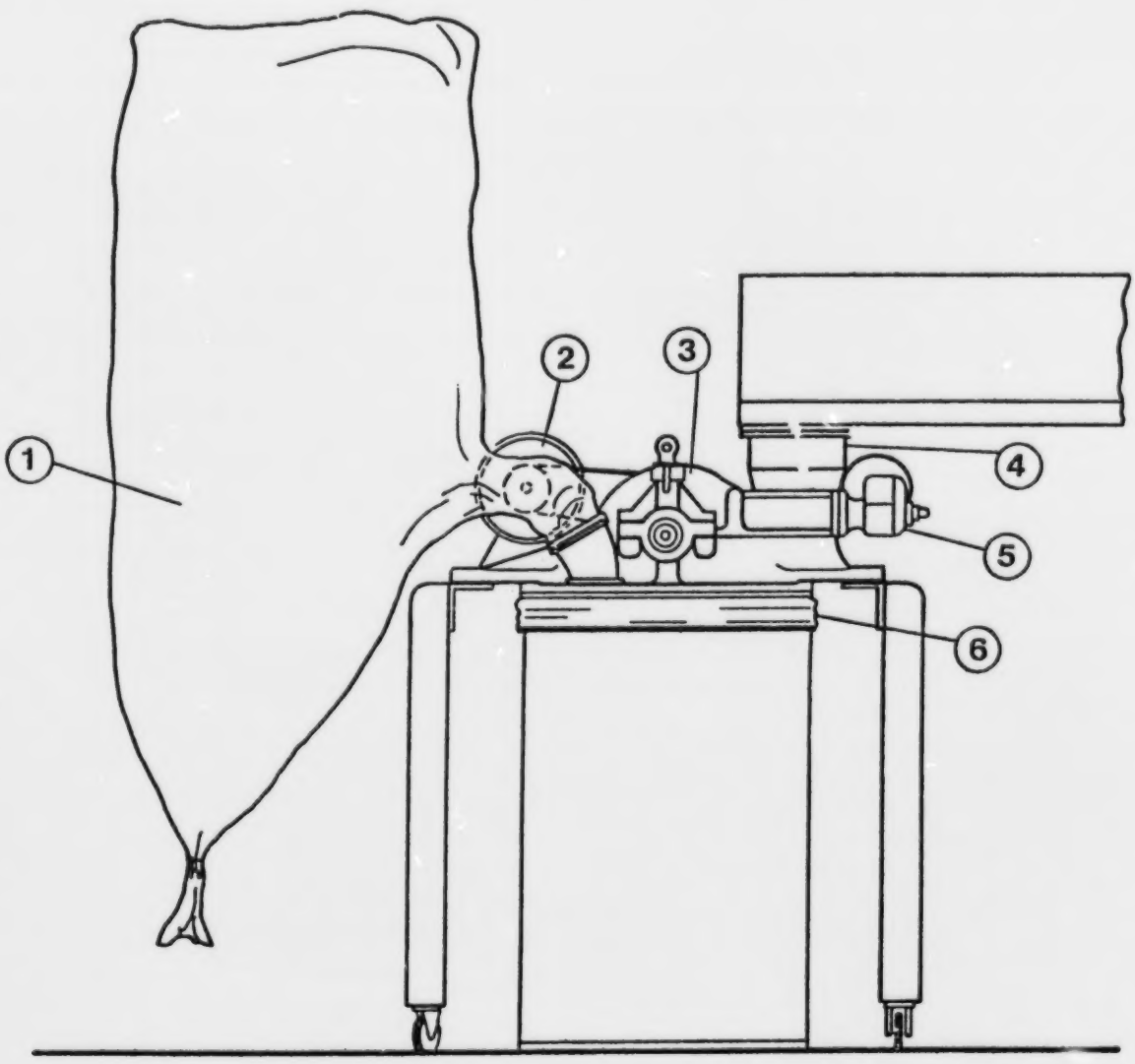
The major system components can be grouped under five major headings as follows:

a. Conveyor
   (1) Conveyor Housing (**9**, Figure 3)
   (2) Conveyor Screw (**6**, Figure 3)
   (3) Impeller (**5**, Figure 3)
   (4) Baffle (**11**, Figure 3)
   (5) Feed Hopper (**10**, Figure 3)
   (6) Door Latches (**4**, Figure 3)
   (7) Transition Piece (**4**, Figure 4)
   (8) Drive Guard (**12**, Figure 3)
   (9) Door (**2**, Figure 3)
   (10) Tadpole Gasket (**13**, Figure 3)
   (11) Proximity Switch, Conveyor Interlock (**15**, Figure 3)



1. CONTROL PANEL (see Fig. 8)
2. SIDE OPENING CLEANOUT DOOR
3. LIN INJECTION TUBE
4. DOOR LATCH
5. IMPELLER
6. S.S. CONVEYOR SCREW
7. CONTROL VALVE BOX ASSEMBLY (see Fig. 5)
8. LIN SPRAY MANIFOLD
9. CONVEYOR HOUSING
10. FEED HOPPER
11. BAFFLE
12. DRIVE CHAIN GUARD
13. TADPOLE GASKET
14. SCR VARIABLE SPEED DRIVE MOTOR
15. PROXIMITY SWITCH, SAFETY INTERLOCK

FIGURE 3 STANDARD CRYO-GRIND SYSTEM



1. NITROGEN GAS RELIEF BAG
2. MILL MOTOR
3. HAMMERMILL
4. TRANSITION PIECE
5. FEED SCREW ASSEMBLY
6. PRODUCT DISCHARGE BAG

FIGURE 4 MILL AREA

b. Conveyor Drive
   (1) SCR Drive (**14**, Figure 3)
   (2) Gear Box (**2**, Figure 6)
   (3) Friction Clutch (**6**, Figure 6)
   (4) Driven Sprocket (**8**, Figure 6)
   (5) Roller Chain (**4**, Figure 6)
   (6) Drive Sprocket (**9**, Figure 6)
   (7) Gear Box Mounting Bolt (**1**, Figure 6)
   (8) Conveyor Shaft (**7**, Figure 6)
   (9) Gear Reducer Shaft (**10**, Figure 6)

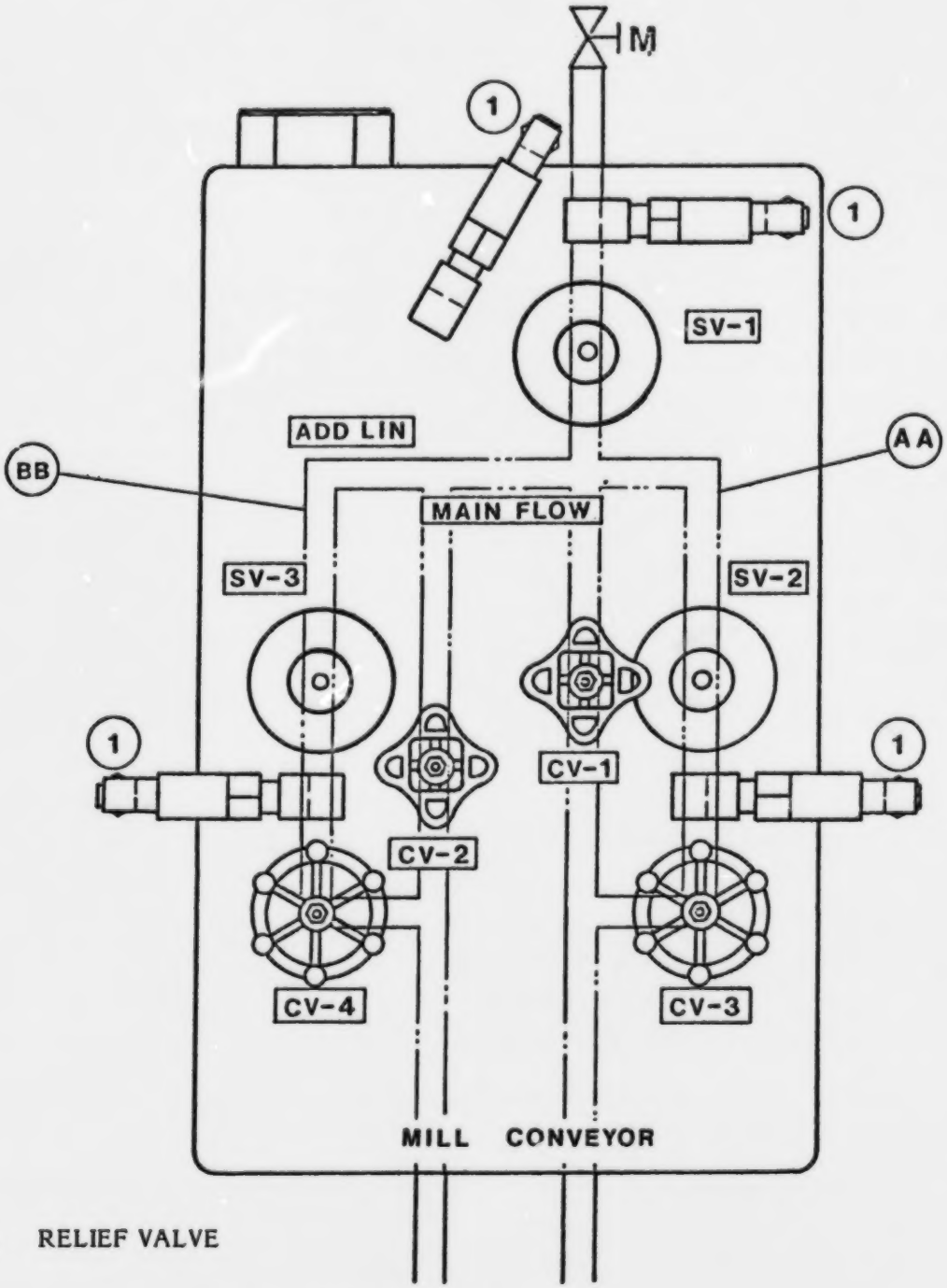
c. Control Valve Box Assembly (Figure 5)
   (1) Main Valves (CV-1, CV-2)
   (2) Main LIN Shutoff Solenoid (SV-1)
   (3) By-pass Valves (CV-3, CV-4)
   (4) By-pass Solenoids (SV-2, SV-3)
   (5) Relief Valves (external)
   (6) Durable Fiberglass Box

d. Mill
   (1) Hammermill (**3**, Figure 4)
   (2) Feeder Screws (**1**, Figure 7)
   (3) Feeder Motor (**5**, Figure 4)
   (4) Mill Motor (**2**, Figure 4)
   (5) Hammers (**2**, Figure 7)
   (6) Nitrogen Gas Relief Bag (**1**, Figure 4)
   (7) Product Discharge Bag (**6**, Figure 4)
   (8) Proximity Switch, Mill Head Interlock (**5**, Figure 7)

Note: This particular size-reduction mill is shown for illustration purposes. Many different types of size-reduction mills have been adapted to "Cryo-Grind" systems.

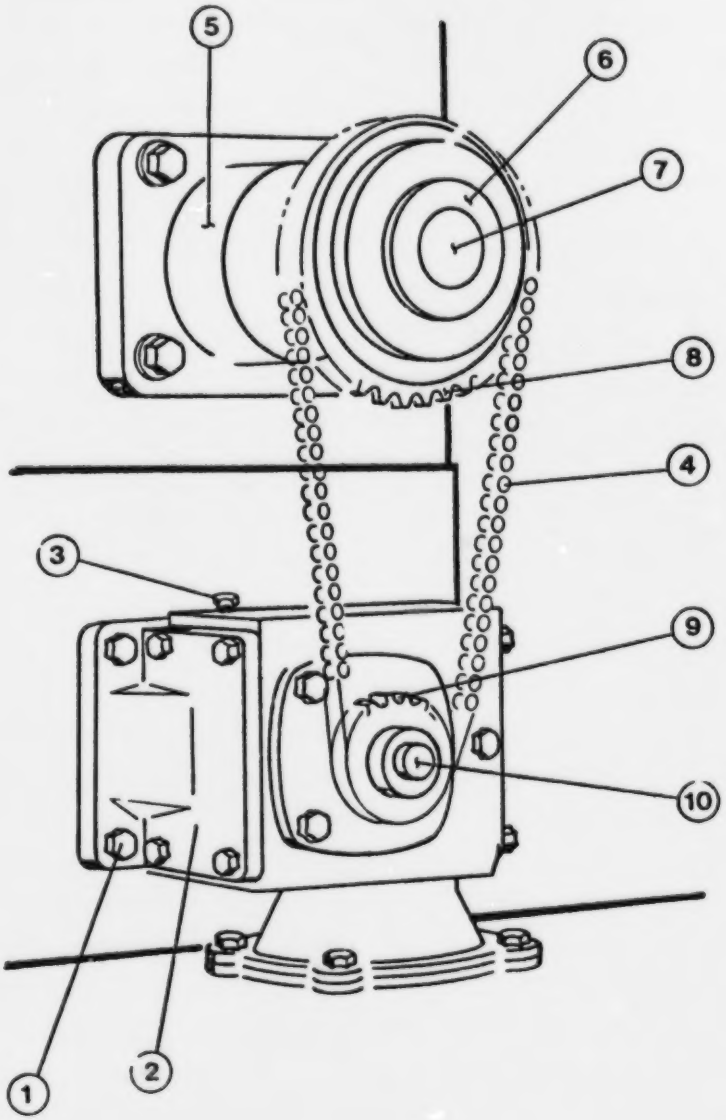
e. Control Panel (Section 3, OPERATION, discusses the control panel components in detail).

   (1) Automatic temperature control system for both the mill and the conveyor: (i) Amber panel lights for indicating additional liquid nitrogen flow; (ii) Two temperature controllers with analog temperature indication.



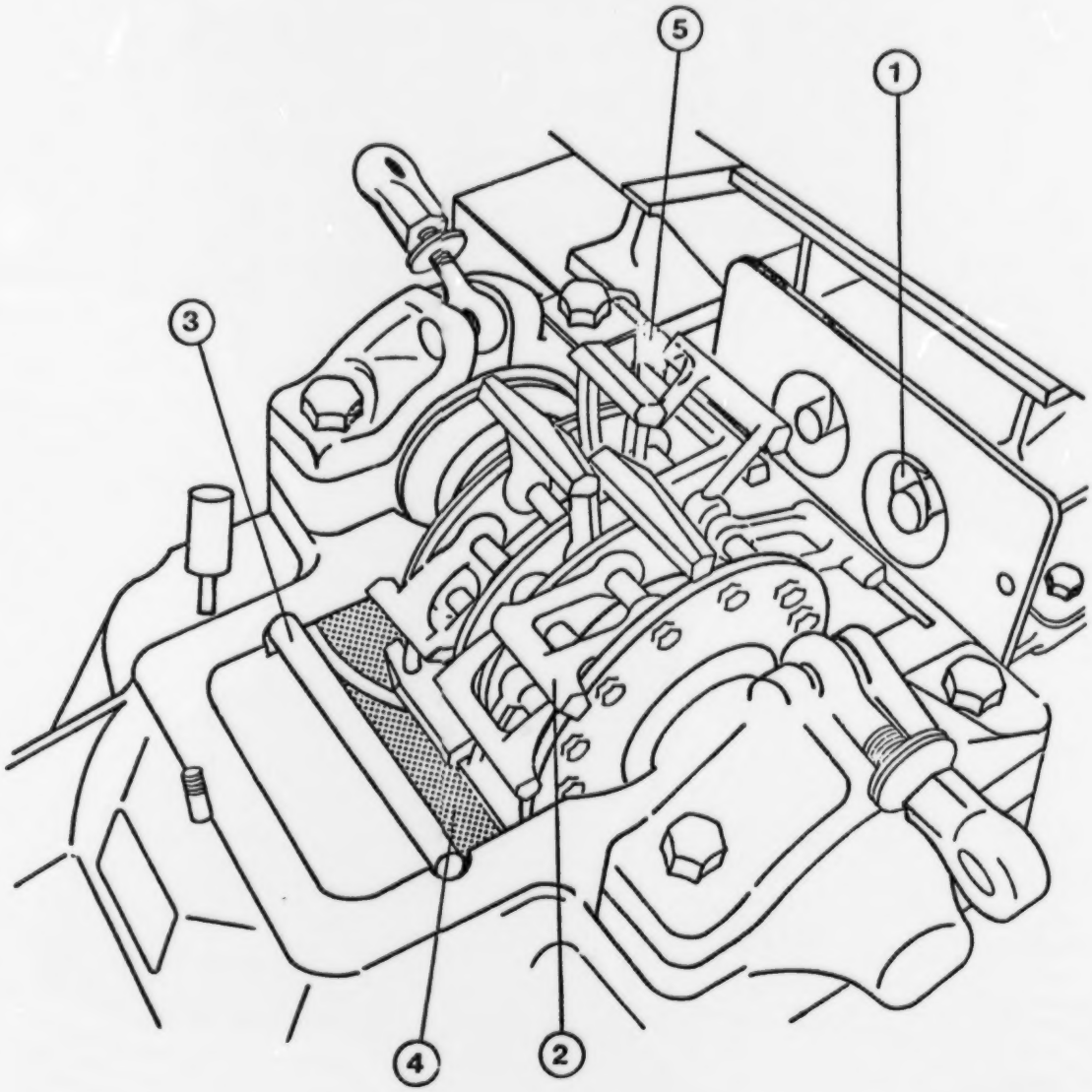
1. RELIEF VALVE

FIGURE 5 CONTROL VALVE BOX ASSEMBLY



1. GEAR BOX MOUNTING BOLT
2. GEAR BOX
3. GEAR BOX VENT PLUG
4. ROLLER CHAIN
5. HEAVY DUTY BEARING
6. FRICTION CLUTCH
7. CONVEYOR SHAFT
8. DRIVEN SPROCKET
9. DRIVE SPROCKET
10. GEAR REDUCER SHAFT

FIGURE 6 CONVEYOR DRIVE SYSTEM



1. FEED SCREWS
2. HAMMERS
3. STAINLESS STEEL DUST SEAL
4. PRODUCT RETAINING SCREEN
5. MILL HEAD INTERLOCK PROXIMITY SWITCH

FIGURE 7 MIKRO-PUL MILL

(2) "Auto" and "Hand" mode selector switch, and system: (i) Blue light indicating the "Auto" mode.

(3) Automatic conveyor speed control system: (i) Conveyor motor armature; DC voltage indicator.

(4) Ammeter controller for overload protection: (i) Overload indicating light.

(5) Exhaust System Interlock.

(6) Pocket Holder to accommodate an oxygen analyzer.

(7) Main Motor circuit breakers.

Note: The Control Panel is designed to accommodate additional control relays for auxiliary equipment.

2.3 Conveyor

Refer to Figure 3. The cooling conveyor chamber (9) consists of a stainless steel trough and outer cover separated by 7.6 cm of rigid urethane foam insulation to minimize heat input and conserve liquid nitrogen.

The conveyor door (2) is made of the same materials as the conveyor chamber. It constitutes the entire front side of the chamber and pivots at the bottom on a full-length hinge. The door is secured in a closed position by three adjustable hold-closed latches (4) located at the top and at each end of the conveyor. A tadpole gasket (13) provides a seal between the door and the conveyor chamber opening.

The conveyor screw (6) is located inside the chamber. A baffle (11) at the inlet to the conveyor screw, a specially designed impeller (5) at the discharge end, and a specially designed conveyor screw ensure direct contact with liquid nitrogen and continuous mixing of the material as it passes through the conveyor chamber.

The drive end of the conveyor screw is pinned to a solid shaft, which is keyed to the driven sprocket (8, Figure 6) and is supported by a flanged, tapered roller bearing mounted to the drive end of the chamber. The discharge end of the conveyor screw is supported by, and rotates on, a solid shaft that protrudes through the chamber wall.

The loading hopper (10) is attached over the opening in the top of the chamber. A "transition" piece (4, Figure 4) is bolted between the mill feed screw assembly and the conveyor assembly with a preformed gasket at each joint.

A safety interlock (15) prevents the operation of the conveyor screw and nitrogen flow when the door (2) is opened. The interlock is a self-contained proximity switch.

2.4 Conveyor Drive

The conveyor drive is mounted on the right end of the conveyor chamber, when viewed facing the chamber door. An SCR controlled drive motor (**14**, Figure 3) powers a drive sprocket (**9**, Figure 6) through a gear reducer (**2**, Figure 6). A roller chain (**4**, Figure 6) connects the drive sprocket to a friction clutch sprocket (**8**, Figure 6) mounted on the conveyor drive shaft (**7**, Figure 6). The friction clutch (**6**, Figure 6) on the conveyor sprocket protects the drive system from overload should material become jammed inside the conveyor. A speed control knob (SPEED ADJ) on the control panel is used to vary the speed of the conveyor screw.

A stainless steel guard enclosure (**12**, Figure 3) covers the entire drive assembly. Access to the drive assembly can be made by removing the cap screws holding the guard cover. ***The conveyor should never be operated unless the guard cover is in place.***

2.5 Control Valve Box Assembly

Refer to Figure 5. The control valve box assembly is a durable fiberglass box containing liquid nitrogen (LIN) metering valves (CV-1, CV-2, CV-3, and CV-4) and LIN control solenoids (SV-2, SV-3) for nitrogen flow control. The main nitrogen shutoff valve (SV-1) is electrically controlled by an On-Off operator (**4**, Figure 8) on the control panel. The bypass system, consisting of one metering valve (CV-3, CV-4) and one solenoid (SV-2, SV-3) in each leg, is the temperature control segment of the valve box assembly. Bypass "AA" is the temperature control leg for the conveyor cooling chamber. The electric On-Off solenoid (SV-2) is automatically operated by a temperature controller on the control panel (**14**, Figure 8). Bypass "BB" is the temperature control leg for the Mikro-Pul mill. The electric On-Off solenoid (SV-3) is also automatically operated by a temperature controller (**13**, Figure 8).

2.6 Size-Reduction Mill

A hammermill or attrition mill is generally used in the cryogenic grinding system. As an example, a Mikro-Pulverizer hammermill is shown (Figure 7) attached to the "Cryo-Grind" system. The mill has stainless steel contact parts. It consists of a rotor assembly fitted with stellite-tipped hammers (**2**, Figure 7) and is belt-driven by a 14.9 kW electric motor (**2**, Figure 6). Feedscrews (**1**, Figure 7), driven by a 0.37 kW electric motor (**5**, Figure 6), convey the embrittled product to the mill. The mill and feedscrew assembly are attached to the cooling conveyor chamber by a "transition" piece (**4**, Figure 6). The

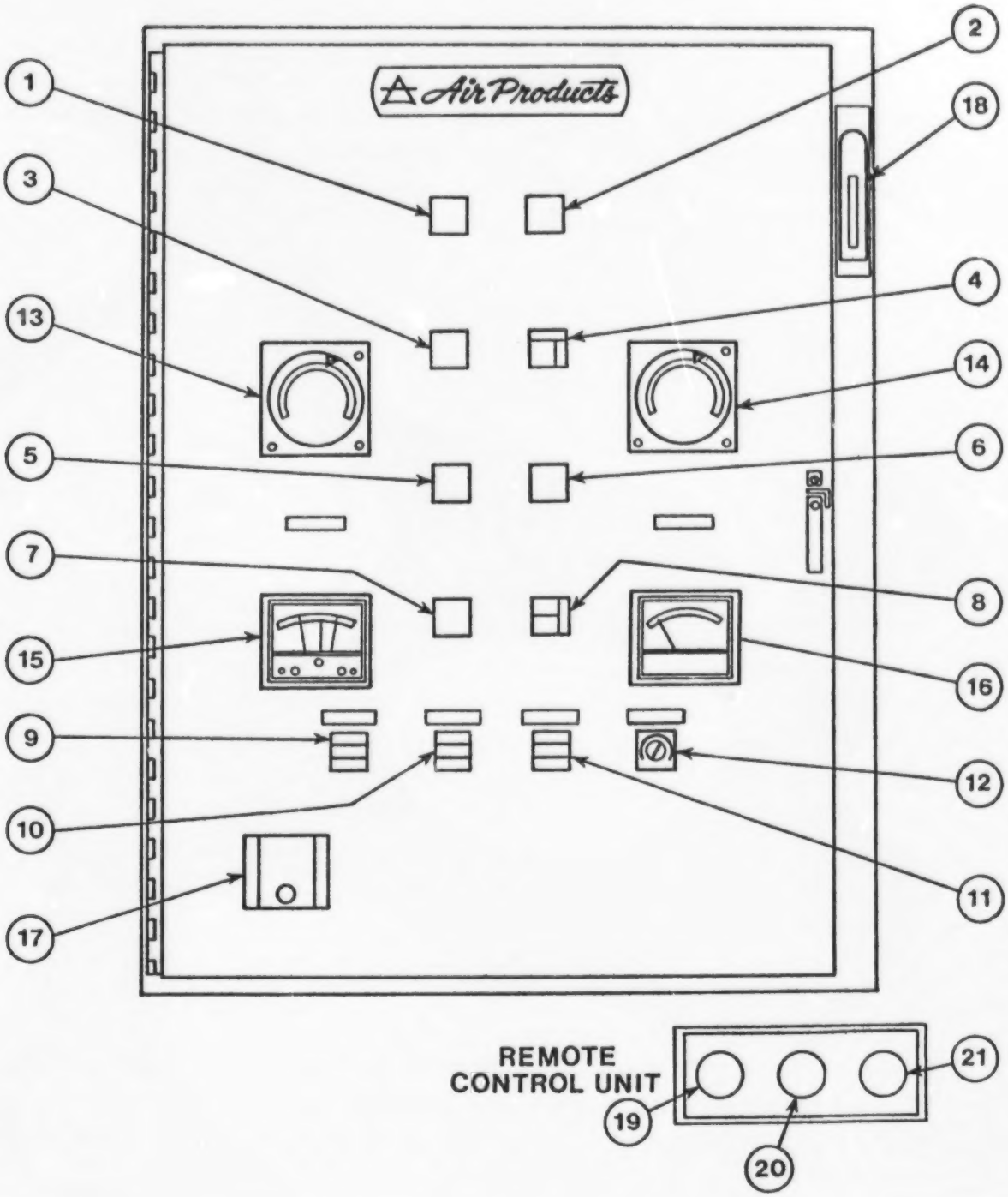


FIGURE 8 COMPLETE CONTROL PANEL

mill assembly is supported by a metal stand. To control dusting, a nitrogen gas relief bag (**1,** Figure 4) and product discharge bag (**6,** Figure 6) are attached to the mill. A safety interlock (**5,** Figure 7) prevents turning on and operation of the mill and LIN flow when the mill head (**7,** Figure 6) is off. The safety interlock (**5,** Figure 7) is a self-contained proximity switch.

2.7 Control Panel Description

Refer to Figure 8.

1. EXHAUST FAILURE. Red indicating light.
2. OVERLOAD. Red indicating light.
3. POWER ON. Red indicating light.
4. MAIN LIN. 2 push-button operator with red "ON" light.
5. ADD. LIN ON. Amber indicating light.
6. ADD. LIN. ON. Amber indicating light.
7. AUTO. Blue indicating light.
8. OFF-HAND-AUTO/Selector Switch.
9. MILL MOTOR. 2 push-button operator with amber "ON" light.
10. FEEDSCREW. 2 push-button operator with amber "ON" light.
11. CONVEYOR. 2 push-button operator with amber "ON" light.
12. SPEED ADJ. The control knob adjusts the voltage supplied to the conveyor screw DC drive motor and thereby controls the speed of the conveyor screw.
13. MILL CONTROLLER. The mill temperature controller has an operating range between -212 ℃ and 37.8 ℃. This indicator monitors the temperature sensed by the thermocouple mounted at the discharge end of the Mikro-Pulverizer Mill. Refer to the "Cryo-Grind" technical manual, Appendix, for further information about this indicator-controller.
14. CONVEYOR CONTROLLER. This controller is the same model as the mill controller. It monitors the temperature sensed by the thermocouple mounted at the discharge end of the conveyor cooling chamber.
15. AMMETER/CONTROLLER. The mill current is indicated on the ammeter relay. The ammeter relay is a protection device for the mill.
16. CONVEYOR ARMATURE. The DC voltmeter indicates the voltage supplied to the conveyor drive motor.

17. POCKET HOLDER. The pocket holder is sized to accommodate the oxygen analyzer supplied with the system.

18. QUICK DISCONNECT SWITCH. Power (440 volts) flows through the disconnect switch (17), supplying power to the transformer, the mill motor starter, and the mill feeder motor starter. The transformer provides 115 volts to the various control circuits.

3 OPERATION

Many variables affect the operation of the system and product quality. It is therefore not possible to give precise operating guidelines. Each type of material to be ground must undergo several trials to determine the optimum operating parameters that will produce the desired results.

The following system variables can affect the results obtained with the "Cryo-Grind" system:

a) type of material to be processed,
b) temperature of material exiting the grinding chamber,
c) temperature of material exiting the conveyor,
d) speed of the cooling conveyor,
e) type of hammers in the mill,
f) horsepower of mill motor,
g) speed of mill rotor assembly,
h) type of retaining screen, and
i) size of retaining screen openings.

The disclosure of further operating information is restricted by Air Products and Chemicals Inc. However, Air Products and Chemicals Inc. will make all such information available to each equipment purchaser.

Table 1 summarizes some performance data for cryogenic grinding of several materials. While this Table reflects a wide range of compounds, many polymers will produce different results, depending on formulation.

TABLE 1 TYPICAL RESULTS WITH CRYO-GRIND SYSTEMS

Type of Material	Production Capacity (kg/MJ)	Nitrogen Consumption (kg/kg)	Product Particle Size (US Standard Mesh)
Nylon 11	2.5	1.8	70
Nylon 6	2.7	2.5	100
LD Polyethylene	2.5	1.0	50
LD Polypropylene	3.4	1.25	50
PVC Film	5.1	1.0	60
Flexible PVC	4.2	0.7	50
Silicone	1.7	2.5	80
Viton	2.0	1.8	100
Neoprene	2.5	2.5	60
Nitrite	1.4	3.6	100
SBR	2.5	0.7	40

4 WASTE INVENTORY AND APPLICATIONS

4.1 Rubber

In 1973, there were 106 plants manufacturing rubber products in Canada as part of Standard Industrial Classification 162 "Rubber Product Industries"; of these, 73 were located in Ontario. Tables 2 and 3 indicate the amount of waste generated by these industries during 1975. Summarizing this information, it can be said that approximately 1,590 tonnes per year of scrap rubber are potentially available for recycling in Canada (1,130 tonnes in Ontario). Furthermore, Table 4 indicates that scrap quantities will increase substantially over the next decade.

Cryo-ground rubber is primarily used as an extender for "virgin" compound, thus reducing raw material requirements. In many cases, reincorporation rates up to 20% are acceptable with particle size ranging from 600 microns to 75 microns.

A few examples of the effects of reincorporation rates on physical properties are shown in Table 5. While these results were acceptable to a particular user, it should be mentioned that they are only guidelines. Specific compounds must be judged on their own merits.

Firms using cryogenically ground rubber suggest that the powder be incorporated as close as possible to the end of mixing, to avoid possible scorching. Several companies have also found that the composites showed improved flow characteristics in transfer and extrusion molding operations.

4.2 Plastic

During 1974, the plastic industry in Ontario discarded over 16,800 tonnes of polymer. Table 6 illustrates the amount of scrap generated for each resin type used in Ontario.

Most plastic processors can recycle scrap if it is granulated to a chip or pellet size. However, many applications, such as PVC film and co-polymers, require a much smaller particle size (less than 30 mesh) for recycling purposes. Ambient temperature grinding would not only cause detrimental changes in physical properties, but result in unacceptable production rates.

The portion of plastic scrap available for cryogenic recycling in Ontario is estimated to be over 1,800 tonnes annually.

TABLE 2 WASTE AND SCRAP RUBBER BY SOURCE INDUSTRY, 1975

	(t)
Transportation (tires & tubes, hose, V-belt, molded goods, etc.)	450 - 540
Industrial	140 - 160
Agriculture	23 - 45
Household and furnishing	450 - 680
Wire and cable	small
Footwear and apparel	230 - 340
Total waste and scrap	1,290 - 1,770

TABLE 3 WASTE AND SCRAP RUBBER BY POLYMER TYPE

	(t)
SBR latex	500 - 775
Other SBR	320 - 450
Polybutadiene	115 - 135
Butyl rubber	35 - 45
Other synthetics	70 - 115
Natural rubber	225 - 365
Reclaim rubber	35 - 45
Total waste and scrap	1,300 - 1,925

TABLE 4 PROJECTED UNRECOVERED POLYMER LOSSES FROM RUBBER FABRICATION

	1975 ($t \times 10^2$)	1980 ($t \times 10^2$)	1985 ($t \times 10^2$)	1990 ($t \times 10^2$)
Atlantic Provinces	0.9 - 1.4	1.4 - 1.5	1.8 - 2.7	1.8 - 3.2
Quebec	2.7 - 3.6	3.2 - 5.0	4.5 - 6.8	5.0 - 8.2
Ontario	8.6 - 12.7	11.4 - 17.7	15.9 - 23.6	18.1 - 28.6
Prairie Provinces	0.5 - 0.5	0.5 - 0.9	0.5 - 0.9	0.5 - 1.4
British Columbia	0.5 - 0.5	0.5 - 0.5	0.5 - 0.5	0.5 - 0.5
Total scrap/waste	13.2 - 18.6	16.8 - 25.9	23.2 - 34.5	25.9 - 41.8

TABLE 5 EFFECTS ON PHYSICAL PROPERTIES OF CRYOGENICALLY GROUND RUBBER

Compound	Butyl	Natural	Nitrile	Poly-acrylate	SBR	Silicone
PARAMETERS						
Cured Powder Addition, %	20	20	15	15	10	10
Particle Size[1], µm U.S. Standard Mesh	250	250	250	150	600	600
PROPERTIES						
Hardness, Shore A, Pts.	55	49	70	66	74	60
% Change[2]	0	0	0	+1.5	+1.4	-6.2
Tensile Strength, MPa	12.14	19.53	10.42	7.59	14.88	4.08
psi	1,760	2,830	1,510	1,100	2,157	592
% Change	-7.3	-1.4	+0.7	-1.8	-12.2	-21.2
Elongation, %	650	550	400	180	258	225
% Change	-7.1	0	-2.4	0	-6.1	-10.0
Compression Set[3], % Set	N/A	N/A	N/A	N/A	15	16
% Change					-11.1	0

1. Particle size refers to representative samples of which 96% are smaller than size shown.
2. Indicates percent change in physicals from those of the virgin compound.
3. At 22 hours @ 121°C for SBR and at 70 hours @ 177°C for silicone.

N/A - Property Not Tested.

TABLE 6 WASTE AND SCRAP PLASTICS IN ONTARIO BY RESIN TYPES
(figures represent thousands of kg per annum)

Resin	Total Reported	Recycled At Source	Sold or Transferred	Balance
ABS	1,369	689	249	430
Acrylics	297		73	225
Cellulosics	24			24
Polyester	103	70		33
Nylon	15			15
Polyethylene	11,790	7,207	1,462	3,120
Polypropylene	307	23	34	250
Polystyrene	5,108	2,971	209	1,927
Polyvinylchloride	5,899	1,707	1,955	2,236
Mixed Vinyl	450		14	437
Mixed Thermoplastics	3,238	304	388	2,547
Polyurethane	4,175		767	3,408
Mixed Polyester	6,015		4,549	1,466
Thermosets	689			689
Total	39,479	12,971	9,700	16,807

5 ECONOMIC EVALUATION

The true test of a particular process lies in its operating economics. During the developmental phase of this program, equal emphasis was placed on process economics and process capability. As is the case with cryogenic systems, the liquid nitrogen consumed represents a sizable portion of the operating costs. Consequently, a significant effort was directed toward optimizing the system for minimum nitrogen use.

Process economics have been developed for a typical cryogenic recycling facility using the data obtained from the demonstration plant. These economics are based solely on the cost of the basic operating equipment necessary in the production facility. They do not include the manpower to load or package the product, conveyors, dust collection equipment, etc. These would vary for each facility and were therefore excluded (Table 7).

5.1 Savings to the Customer

The savings to the customer differ substantially from one manufacturer to another. Many factors can have a bearing on recycling costs. Some of the obvious considerations include: transportation, increase in manpower, additional production machinery, and handling equipment. In most cases, however, the primary factor is the cost of the "virgin" compound. Raw materials cost from $0.66/kg for materials like SBR to over $2.20/kg for silicones, and can go as high as $77.00/kg for Viton. A quick comparison of recycled scrap costs to raw material costs clearly shows the economic incentives provided by cryogenic grinding.

5.2 Financial Projections

Notes:

1. -Production capacity is 73 tonnes per month.
   -Usage factor is 0.625 or 45 tonnes per month.
2. Selling price - $0.44/kg
3. Additional machine purchased after 2 1/2 years.
4. Labour cost - 3 men per machine ($12/h - 160 h/month).
5. Nitrogen cost - $0.77/kg.
6. Nitrogen consumption - 1.3 kg/kg of product.
7. Building rental includes 370 m^2 utilities, property taxes and maintenance.
8. Basic Operating Equipment: $110,000.

TABLE 7 FIVE-YEAR PROJECTED STATEMENT OF INCOME

Year	1	2	3	4	5
SALES	$240,000	$240,000	$360,000	$480,000	$480,000
COST OF SALES					
Nitrogen	42,000	42,000	63,000	84,000	84,000
Packaging	6,000	6,000	9,000	12,000	12,000
Insurance	2,400	2,400	3,600	4,800	4,800
Base facility charge	10,800	10,800	16,200	21,600	21,600
Labour	69,120	69,120	103,680	138,240	138,240
Maintenance	3,600	3,600	5,400	7,200	7,200
Depreciation and interest	20,400	20,400	30,600	40,800	40,800
	$154,320	$154,320	$231,480	$308,640	$308,640
GROSS PROFIT	85,680	85,680	128,520	171,360	171,360
GENERAL EXPENSES					
Building rental	12,000	12,000	12,000	12,000	12,000
Towmotor rental	4,200	4,200	6,300	8,400	8,400
Legal and accounting fees	2,400	2,400	3,000	4,800	4,800
Interest	3,000	3,000	4,500	6,000	6,000
Telephone	1,200	1,200	1,500	2,400	2,400
Bank charges	780	780	780	1,560	1,560
Office supplies	780	780	1,000	1,560	1,560
Advertising	1,200	1,200	1,500	2,400	2,400
Travel and entertainment	1,200	1,200	1,800	2,400	2,400
Truck lease	5,400	5,400	8,100	10,800	10,800
Truck - gas, oil and repairs	4,800	4,800	6,200	9,600	9,600
Miscellaneous	2,400	2,400	3,600	4,800	4,800
	39,360	39,360	50,280	66,720	66,720
INCOME BEFORE INCOME TAXES	46,320	46,320	78,240	104,640	104,640
INCOME TAXES @ 24%	11,000	11,000	19,000	25,000	25,000
PROJECTED NET INCOME	$ 35,320	$ 35,320	$ 59,240	$ 79,640	$ 79,640

6 ENERGY ANALYSIS

The Gross Energy Requirement (GER) concept was used to determine the energy balance for this project. The Gross Energy Requirement is the amount of energy source which is sequestered in the process of making goods or services. The value of GER is the gross enthalpy of all the naturally occurring energy sources which must be consumed in order to make the goods.

The following assumptions were applied for the purpose of this analysis.

1. Due to the large number, complexity and proprietory nature of plastic and rubber formulations, the following average GER values were used as material energy figures:

   Average GER of plastics 93,400 kJ/kg

   Average GER of rubber 162,810 kJ/kg

2. Recycled scrap will be used as virgin compound replacement.
3. GER of Liquid Nitrogen is 11,406 kJ/kg of liquid.

The energy savings attributable to cryogenic recycling may be calculated by subtracting the total energy used in the recycling process from the gross energy requirement of the polymers. In the case of cryogenic grinding, the processing energy may be obtained by adding the GER of the liquid nitrogen and the electricity consumed. All other inputs except transportation are small and insignificant. The energy associated with transportation to and from the recycling facility is more than offset by the energy required for transportation to and operation of a waste disposal site.

Based on the calculations in Table 8, the total estimated annual energy savings for cryogenically recycling 680 tonnes per year of a 50/50 mixture of plastic and rubber would be 7.65×10^{10} kJ or 1.9×10^{6} L of crude oil equivalent.

TABLE 8 ENERGY ANALYSIS

Gross Energy Requirement (GER) of Polymers =

$$0.5\,(93{,}040 + 162{,}810)\ \frac{kJ}{kg} \times 680{,}389\ kg = 8.7 \times 10^{10}\ kJ$$

Processing Energy = GER of Liquid Nitrogen + GER of Electrical Input

$$= \left((1.3 \times 11{,}406)\ \frac{kJ}{kg} + \left(554\ \frac{kJ}{kg}\right)\right) \times 680{,}389\ kg$$

$$= 1.05 \times 10^{10}\ kJ$$

Energy Savings = GER of Polymers - Processing Energy

$$= 8.7 \times 10^{10} - 1.05 \times 10^{10}$$

$$= 7.65 \times 10^{10}\ kJ$$

Crude Oil Equivalent

$$\frac{7.65 \times 10^{10}\ kJ}{39{,}451\ kJ/L} = 1.9 \times 10^{6}\ L$$

- Based on a throughput of 680 tonnes of a 50/50 mixture of plastic and rubber.
- Cryo-grind electrical requirements 554 kJ/kg.
- Average LIN consumption 1.3 kg/kg of scrap.
- Average Heat of Combustion of Crude Oil 39,451 kJ/L.

7 ENVIRONMENTAL IMPACTS

The proposed system is primarily aimed at recycling valuable resources and will result in benefits to the environment which are summarized below:

- Resource conservation resulting in reduced environmental damage from resource extraction and processing.
- Reduced burden on landfill operations.

8 RESULTS

The project successfully demonstrated that a cryogenic grinding facility can provide significant potential for recovering non-renewable resources and reducing the amount of solid waste dumped in landfills. The establishment of a cryogenic grinding facility in Ontario which allows plastic and rubber industries to economically recycle scrap, to make more efficient use of their raw materials, and to reduce overall operating costs has, in some cases, improved the competitive position of select rubber and plastic manufacturers. Furthermore, the Custom Cryogenic Grinding Corp. has created jobs and contributed to the Canadian and Ontario economies in general.

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